

## AN EXPERIMENTAL SIMULATION OF CROSSFLOW COAL GASIFICATION

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### ABSTRACT

A novel combustion test-pot facility was constructed and operated so as to simulate crossflow coal gasification with steam at ambient pressure. The test pot was fully instrumented to allow transient measurements of pressure drop, weight change of the bed, and product gas composition. In addition, the temperature front within the bed was tracked as a function of both time and position. Experiments were conducted at different air and steam flow rates in a packed particle bed of coke. The weight of an average coke charge was approximately 35 pounds and the fuel utilization rate ranged between 7.8 and 22 lb/ft<sup>2</sup>-hr. Based on the experimental results, energy and mass balances were performed and closed to about 90%. Data obtained were used to verify a computer simulation of the process.

### 1. INTRODUCTION

The most common commercial coal gasification system in use today is the counter-flow moving bed system. In this system, the coal feedstock moves downward and passes through four idealized zones in the gasification process. These zones in order from the top to the bottom of the bed are drying, pyrolysis, gasification and combustion. However, most moving-bed units are size-limited and several must be operated in parallel for larger throughputs.

An alternate approach to the design of a large-scale coal gasification system would be to borrow established technology from a similar process. One such process has long been utilized to sinter iron ore and produce a "strong clinker" suited for feed stock in a blast furnace. The sintering machine most commonly used today is a modification of the Dwight-Lloyd continuous sintering machine, formerly used only in the lead and zinc industry [1]. Originally developed in the early 1900's, the machine consists of a strong structural steel frame supporting two large gears and steel tracks. A system of pallets, or trays, with perforated bottoms is driven by these gears at a speed of 1 to 3 feet per minute. The sintering machine for iron ore may be 6 to 12 feet wide by 90 to 168 feet in length with pallets to hold the charge. Underneath the pallet train is a series of suction boxes which are connected with a fan to induce a downdraft through the perforated bottom and ore charge. Located at the input of the machine is a burner which serves to initiate the sintering process by igniting the top layer of charge. The charge is typically a mixture of ore particles up to 1/4-inch in diameter, flux, to aid in the agglomeration, and fuel, such as coke. The charge layer may be 6 to 12 inches deep. The largest machines will treat as much as 4500 tons of ore per day.

The possible application to coal gasification would be the replacement of the ore charge with coal [2]. The coal particles up to 1/4-inch in diameter would be placed on another layer of inert material, such as limestone, roughly 1/2-inch in diameter. This inert material would serve to protect the grate thermally, support the smaller coal particles, trap out particulates and possibly aid in sulfur removal from the product gas stream.

The main objectives of the work presented here were the design, construction and start-up of an experimental apparatus that would effectively simulate the crossflow process. The independent variables such as air temperature and flow rate, and relative humidity of the air feed were selectively examined to determine their effect on the exit gas composition and fuel utilization rate. These data will assist in determining the reliability of the experimental test-pot system and its potential for use in future experimental and modelling efforts.

## II. EXPERIMENTAL APPARATUS

A flowsheet of the proposed test-pot facility is shown in Figure 1. Ambient air, fed from a ring compressor, was preheated and humidified before it entered the combustion pot. An orifice plate served as an air flowmeter, while the air was preheated using a steam heater. Supply steam at 30 psig was regulated, using a Kaye MacDonald regulator, to the pressure required to obtain the desired heater temperature. The air was humidified by direct injection of saturated steam. The temperature and relative humidity (RH) of the feed air were measured as the air entered the combustion pot using an Omega RH-20F hygrometer. This instrument is capable of reading temperatures to  $175^{\circ}\text{F} \pm 0.5^{\circ}\text{F}$  and relative humidity to  $95\% \pm 2\%$ . The humidity measurement was backed with a Hygrodyamics L4-4822W sensor and L15-3050 Universal Indicator capable of reading to  $98\% \text{ RH} \pm 1.5\%$ . After the product gas exited the test pot, a sample was taken for analysis and the remainder combusted in an afterburner.

The test pot itself is shown in Figure 2. It consists of a 24-inch o.d. steel pipe, 1/2-inch thick wall, with a 1/8-inch thick stainless steel plate welded to the bottom. The plate is perforated with 3/8-inch diameter holes located on 1/2-inch triangular centers. The pipe is lined with 5 inches of insulation brick refractory, resulting in an inside bed diameter of 13 inches. Pt vs. Pt 10% Rh thermocouples (TC) are placed at 2-inch intervals above a 6-inch layer of non-combustible material. The thermocouples are rated to  $3000^{\circ}\text{F}$  and can be used in oxidizing or reducing atmospheres. The temperature in the coal bed is monitored automatically as a function of time as well as position by means of a Doric Digitrend 220 data logger.

Operating at near atmospheric pressure, the test pot is free-hanging while the transient weight change of the coal is recorded utilizing a load cell. The load cell is a Sensotec model RM-1K, hermetically sealed to withstand humid and corrosive environments and temperature compensated to  $160^{\circ}\text{F}$ . It has a range of 0 to 1000 pounds mass and its stated accuracy is  $\pm 0.2\%$  of full scale or  $\pm 2$  pounds. A Sensotec 450D digital readout with a 0-5 volt recorder output is used in conjunction with the load cell. The separation between the inlet and outlet of the pot is maintained by a water seal which allows the test pot to hang freely and still maintain the division between the inlet and outlet of the bed.

### a) Experimental Procedure

The bed was charged with 35 pounds of coke, resulting in a coke bed density of  $38 \text{ lb/ft}^3$ . Coke, the devolatilized product of coal, was selected as the feedstock for the initial tests as it would produce a less complex gasification product, free of tars and volatile material. For a typical experimental run, the procedure is as follows. The air, fed at 25 CFM and  $77^{\circ}\text{F}$ , is heated to  $140^{\circ}\text{F}$  and humidified to near 100% RH before entering the combustion pot. The air feed is started first and allowed to reach steady state at which point the fuel charge is ignited with charcoal placed at the top of the charge. Ignition of the fuel occurs within 5 to 10 minutes. The data logger is used to record the temperatures at specific time intervals, initially every

minute. The weight change with time as monitored by the load cell is also recorded continuously with a strip-chart recorder. Finally, gas samples from the outlet of the test pot are taken at specific time intervals, every 10 minutes, and analyzed with a gas chromatograph (GC). The GC is a Gow-Mac Series 550 thermal conductivity-type gas chromatograph equipped with a gas sampling valve, series/by-pass column switching valve, one 5A molecular sieve column and one Porapak Q column. The run is considered finished when the combustion front reaches the bottom of the bed. This is tracked via the thermocouples placed at intervals within the depth of the bed, and is also indicated by abrupt changes in the gas composition and the pressure drop across the bed.

### III. RESULTS

#### a) Product Gas Composition

Samples of the product gas were withdrawn from the bottom of the combustion pot at approximately 10 minute intervals. The GC was configured for the detection of  $N_2$ ,  $CO_2$ ,  $H_2$ ,  $CH_4$ ,  $CO$  and  $O_2$ . A representative composition/time profile is shown in Figure 3. After an initial transient period (around 20 minutes for the run in Figure 3), the product gas composition remains essentially constant for the duration of the test. The onset of breakthrough is signalled by an abrupt increase in the  $N_2$  composition late in the run. A typical product gas contained roughly 20%  $CO_2$ , 10%  $CO$ , 10%  $H_2$ , 2%  $CH_4$  and 60%  $N_2$ . The GC was checked before and after each run with a standard calibration gas obtained from Supelco, Inc.

#### b) Weight Change

The transient weight of the bed provided the data necessary to calculate the fuel utilization rate and the rate of progression of the combustion front. Representative data for a typical run are shown in Figure 4. This data, used in conjunction with the transient pressure drop across the bed, permitted the actual weight change with time to be determined.

In all cases, the weight change profiles showed an initial period in which the weight of the bed remained relatively constant, followed by a uniform decrease in weight until the end of the run. The slope of this line when divided by the cross-sectional area of the bed yielded the fuel utilization rate at the conditions of the experiment. This was found to vary from 7.8  $lb/ft^2-hr$  at the lowest air flow rate to 22.1  $lb/ft^2-hr$  at the highest air flow rate. These values are well within the range of those reported for the Wellman-Galusha gasifier with a coke fuel [3]. Comparable results were also found by Essenhigh who reported fuel utilization rates of 5 to 25  $lb/ft^2-hr$  under similar experimental conditions [4].

The fuel utilization rate when multiplied by the density of the packed bed yielded the rate of progression of the combustion front which ranged from 0.06 to 0.13 inches per minute.

#### c) Temperature Profiles

The temperature profiles of a typical experimental run are shown in Figure 5. Such data are useful in determining the progression of the combustion and gasification zones through the bed. A sharp increase in temperature in the early stages followed by a peak as the combustion zone passed, and finally a decrease in slope as the gasification zone passed, are characteristics of all the profiles.

The temperature profiles were used as an alternate method for calculating the

progression of the combustion front through the bed by measuring the time between the temperature maxima at each thermocouple location. The progression of the combustion front determined in this manner was compared with the progression as determined from the weight change data as a check of the load cell instrumentation and as a check on the evenness of the burn. Good agreement was seen in the progression of the combustion front as determined by each method. This would indicate that the combustion front of the fuel bed is burning in a relatively uniform, plug-flow manner.

#### d) Mass and Energy Balances

The calculation of the mass and energy balances was done as a check of the overall performance of the instrumentation.

The mass balance focused primarily on the carbon present in the charge. In order to calculate the carbon balance, it was necessary to obtain the inlet gas flow rate and composition, the outlet gas flow rate and composition, and the length of time the run was in progress. From this information the mass of carbon present in the exit gas could be determined and compared to the mass of carbon that was consumed as calculated from the weight change. Such a balance resulted in closure to over 90% in most cases, indicating that the instrumentation was functioning adequately for the intended purpose.

The energy balances also showed good results, usually accounting for over 90% of the energy released from the coke fuel. Approximately 50% to 55% of the energy leaves the bed in the form of combustables in the product gas. The heat losses to the system were 20% of the energy available, while the energy carried as sensible heat in the product gas accounted for approximately 20% as well. These results are encouraging in showing that the instrumentation and the experimental system are operating reliably.

#### IV. DISCUSSION

For the Wellman-Galusha gasifier with a coke fuel the CO and H<sub>2</sub> concentrations observed in the product gas are 29 mol% and 15 mol% respectively [3]. The data collected from the test pot came to only 50% to 60% of those for the Wellman-Galusha gasifier. Moreover, the heating value reported for the Wellman-Galusha was 130 BTU/ft<sup>3</sup>; the crossflow product gas was only 80 BTU/ft<sup>3</sup>. Also, Essenhight reports CO concentrations of 23 mol% for his similar test-pot studies using a coke fuel [4]. He does not report a value for hydrogen. In an associated modelling effort, both the results of the test pot and the other workers could be predicted by including a reactivity factor in the rate equations to account for variations in feedstock characteristics [5]. Thus differences in product gas composition may reflect variations in the physical and chemical characteristics and hence reactivity of the feedstock.

The test pot responded to changes in air feed to the bed as expected. Under the same steam feed conditions, higher air flow rate resulted in higher combustion temperature and a shorter run time. The test-pot also responded as expected to changes in the steam feed to the bed. High steam rates resulted in lower temperatures in both the combustion and gasification zones. This in turn affected the product gas compositions by suppressing CO production and increasing H<sub>2</sub> production. The lower combustion and gasification temperatures also allowed for more uniform heating of the bed and a more defined and stable gasification zone. Conversely, low steam flows yielded higher combustion and gasification temperatures, with CO production favored and H<sub>2</sub> suppressed.

It should also be noted that CO<sub>2</sub> generated in the combustion zone is not being completely converted to CO as it passes through the gasification zone. Low temperature, short residence time, gas channeling, clinker formation or low fuel reactivity are possible factors affecting conversion.

## V. CONCLUSIONS

The fuel utilization rates for this system were comparable to those for the Wellman-Galusha gasifier [3]. The carbon mass balance resulted in over 90% closure in most cases, a result which is consistent with that reported by other researchers in the gasification area [3,4]. The energy balances show approximately 50% of the energy leaves the gasifier in the form of combustibles. Another 20% of the energy leaves in the form of sensible heat and roughly 20% is lost to the system.

Based upon the data collected and the mass and energy balances performed, the experimental test pot system operated reliably and produced good data.

## REFERENCES

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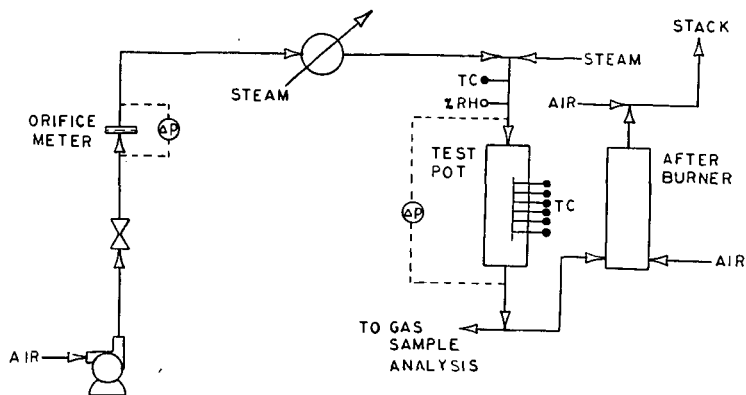


Figure 1. Overall flowsheet of crossflow coal gasification test pot facility.

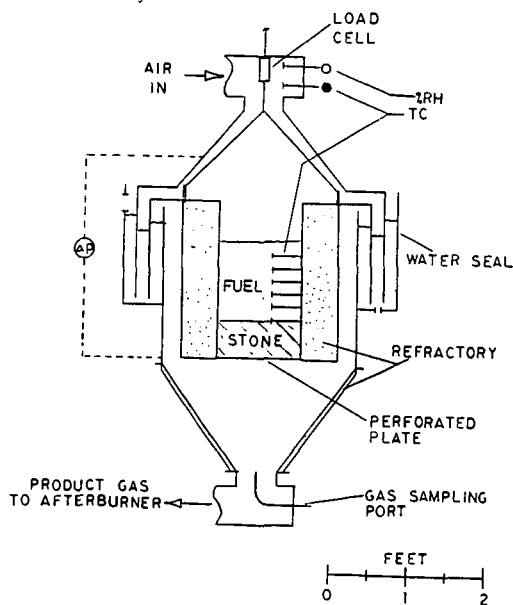


Figure 2. Cross-sectional view showing details of experimental test pot.

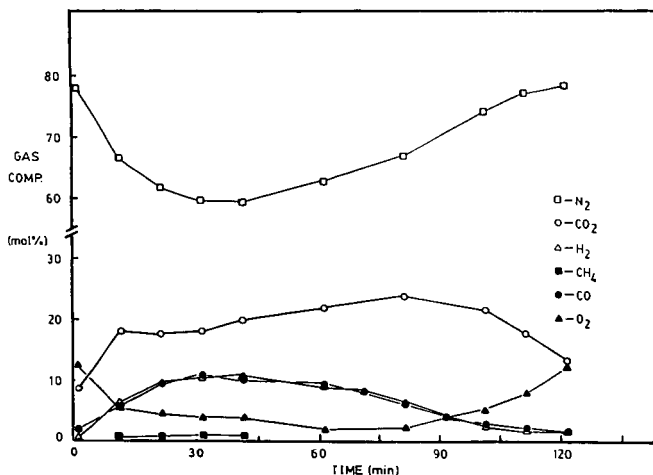


Figure 3. Representative composition/time profiles for major components in product gas stream.

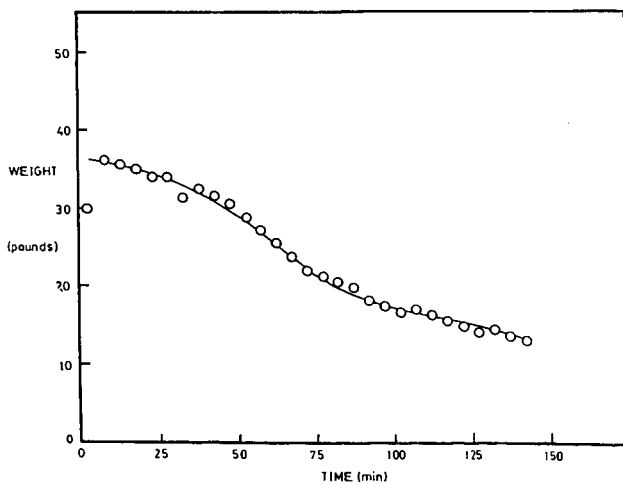


Figure 4. Transient weight change of coke charge for a typical gasification test.

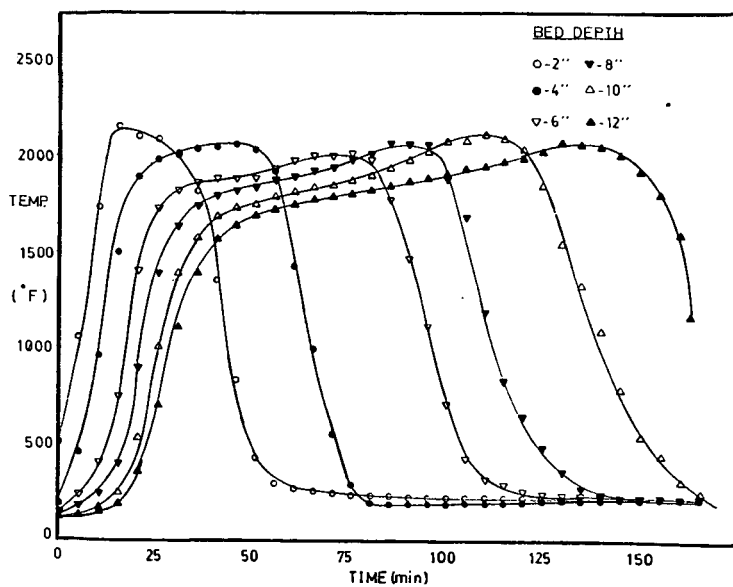


Figure 5. Transient temperature profiles at various bed depths as measured from the top of the bed.